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13. ABSTRACT *(Maximum 200 words)*
Laboratory experiments were carried out to investigate the behavior of a stratified shear layer forced by a contiguous turbulent layer. The aim was to study the interaction of shear with the internal waves generated in the stratified layer, in particular, the absorption of internal waves at the critical layer. A set of complex phenomena appeared in the stratified shear layer, however, masking the critical layer phenomena and signifying several types of instabilities. The stratified turbulence so generated was studied extensively using state-of-the-art flow diagnostic techniques. Several new inferences on the nature of sheared stratified turbulence were also made.

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Report:
AASERT: Critical-Layer Absorption in Stratified Flows
(ONR Contract N00014-94-1-0771)

A comprehensive research program was carried out to understand turbulent mixing in stratified shear flows due to instabilities that are partly resulting from the breakdown of the shear layer due to critical layer absorption. Since it was difficult to separate the critical layer phenomena from other instabilities, mixing due to a combination of instabilities was studied. Laser-Induced Fluorescence, laser-Doppler, acoustic-Doppler and hot-film anemometry and conductivity measurements were used to obtain a unique set of data on turbulence and mixing in stratified shear flows; to our knowledge, these are the most highly resolved entrainment measurements in stratified fluids gathered hitherto. The upper turbulent layer (of thickness D) was driven over the lower dense layer by a disk pump. After some time from the start of the experiment, the flow assumed a configuration wherein a density interface of thickness T across which the buoyancy jump is B is embedded in a thick velocity shear layer of thickness S and velocity jump U. The center of the density interface was offset by a distance d from that of the velocity interface. This stratified shear layer separates the moving upper and stagnant lower layers. Based on dimensional and physical arguments, it was shown that the important governing parameters for the problem are the bulk Richardson number Ri = BD/(U**2) and the frequency ratio F = ND /U. The upper part of the mixed-layer was maintained in turbulent state by wall-induced turbulence whereas turbulence in the lower part was contributed by the turbulent production at the stratified shear layer.

The Richardson numbers used in the experiments were sufficiently large (Ri > 1) that the usual eddy-engulfment mechanism, which is typical of unstratified flows, was not tenable. Since the eddies were too feeble to scour dense fluid from across the interface into the upper layer, the entrainment occurred by local mixing induced by interfacial instabilities that caused the development of an intermediate layer of partially mixed fluid which, in turn, could be engulfed by turbulent eddies. As such, the instabilities at the interface and associated buoyancy flux, the transport of intermediate-layer fluid by turbulent eddies and its homogenization in the upper layer play crucial roles in the mixed-layer deepening process. The first two processes were identified as rate-limiting steps, depending on Ri.

Although interfacial disturbances are of finite amplitude nature, linear stability results could be successfully used to identify interfacial instabilities. Linear stability analysis of the present flow configuration (widely different S, T, D and d) has not been reported, but some related asymptotic cases have been documented recently by Haig & Lawrence (1999, Phys, Fluids,11(6),1459-1468). For D > S, the governing parameters have been identified as the shear-layer Richardson number Ris = BS/(U**2) and the ratio e = d /S. For the present case, both Ris and e are determined by the parameters Ri and F. Haigh & Lawrence predicted instabilities for all Ris, but they conjectured that neither pure K-H nor Holmboe waves may be observable for finite values of e, which should be contrasted from the e = 0 case where a distinct transition from K-H to Holmboe modes is predicted at Ris = 0.046. In the present experiments, nonetheless, for Ris < 0.36 (or Ri < 3.2), the predominant mode was K-H whereas Holmboe modes dominated at Ris > 0.64 (or Ri > 5.8) irrespective of F. Perhaps the most interesting regime is 3.2 < Ri < 5, where both K-H and wave-like instabilities co-exist possibly resonating with each other. These waves resemble one-sided asymmetric Holmboe instabilities found in previous work.

The mixing efficiency (or the flux Richardson number) peaked in this regime, with a maximum of 0.4 at Ri ~ 5. The wave asymmetry decreases with increasing Ri over the range 5 < Ri < 5.8 and at Ri > 5.8 two-sided Holmboe instabilities become dominant. There was an order of magnitude reduction in the entrainment rate beyond Ri = 5, at the transition from the active K-H wave breaking regime to the (intermittently breaking) asymmetric wave regime. This suggests that practical mixed layer models can use Ri ~ 5 as the threshold beyond which there is negligible mixed-layer deepening.

Detailed energy budget and interfacial observations revealed some interesting aspects of internal-wave radiation. Considering a number of possibilities for the excitation frequency, for example, those corresponding to mixed-layer eddies, advection of K-H billows and the range of frequencies induced by secondary instabilities of K-H billows, it was concluded that the most viable internal-wave excitation source is the interfacial swelling events. Locally mixed fluid, generated by interfacial instabilities, causes the interface to swell, leading to an intermediate layer sandwiched between the interfacial layer and the upper mixed-layer, which, in turn, is eroded by the mixed-layer eddies to generate a low frequency event (of the order 0.25-0.5 Hz in the present case). The ensuing thin interface again becomes unstable, causing K-H billowing and swelling. The recurrence of these events acts as the excitation source of internal waves. When Ri < 5, the production rate of intermediate density fluid is faster than or of the same order as their removal by the eddies and thus the intermediate layer is well defined. Estimation of internal-wave radiation based on the frequency of the swelling phenomenon is consistent with that evaluated by the direct measurement of the energy budget. At Ri > 5, the intermediate layer can hardly be detected, implying that the rate of buoyancy transport by eddies exceeds the rate of production of locally mixed fluid by interfacial instabilities. In general, for Ri < 5, the entrainment is turbulent transport limited, for Ri > 5 it is interfacial mixing limited, and at Ri ~ 5 both the transport and mixing rates are comparable yielding the maximum mixing efficiency of approximately 0.4. In 3 < Ri < 5, the intermediate layer buoyancy frequency is of the same order as the forcing frequency of the adjacent turbulent eddies, thus ensuring effective energy transfer to the interfacial area. This, together with mutually resonating K-H and asymmetric waves, appears to be responsible for the higher entrainment (interfacial erosion) rates observed for the two-layer case and largest disparity of entrainment rates observed between two-layer and linearly stratified cases in 3 < Ri < 5.

Publications:

Strang, E.J. and Fernando, H.J.S., "Turbulence and Mixing in Stratified Shear Flows," Journal of Fluid Mechanics, In Press.

Kit, E., Strang, E. and Fernando, H.J.S., "Measurement of Turbulence Near Shear-Free Density Interfaces, " Journal of Fluid Mechanics, 334, 293-314, 1997.